Intense terahertz laser fields on a two-dimensional electron gas with Rashba spin-orbit coupling

J. L. Cheng and M. W. Wu*

Hefei National Laboratory for Physical Sciences at Microscale and Department of Physics[†], *University of Science and Technology of China, Hefei, Anhui, 230026, China*

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The spin-dependent density of states and the density of spin polarization of an InAs-based two-dimensional electron gas with the Rashba spin-orbit coupling under an intense terahertz laser field are investigated by utilizing the Floquet states to solve the time-dependent Schrödinger equation. It is found that both densities are strongly affected by the terahertz laser field. Especially a terahertz magnetic moment perpendicular to the external terahertz laser field in the electron gas is induced. This effect can be used to convert terahertz electric signals into terahertz magnetic ones efficiently.

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Much attention has been devoted to the emerging field of semiconductor spintronics recently.[1,2] An active manipulation of the spin degrees of freedom in Zinc-blend semiconductors, where the symmetry of the spin degrees of freedom is broken due to the lack of inversion center of the crystals, is the central theme of this field. Many external conditions, such as temperature and electric and magnetic fields, can affect the spin coherence and have been discussed extensively both experimentally and theoretically.[2] Among these conditions, terahertz (THz) field, which can efficiently change the electron orbit momentums and significantly modify the electron density of states (DOS), has been applied to spintronics rarely and only very recently,[3,4] although it has been extensively studied in spin-unrelated problems such as the dynamic Franz-Keyldysh effect (DFKE) and optical sidebands.[5,6,7,8,9,10] As an intense THz laser radiation affects the orbit degrees of freedom efficiently, due to the spin-orbit coupling (SOC), it can also effectively affect the spin degrees of freedom. In the present letter we will show how a THz field can induce the spin polarization in a two-dimensional electron gas (2DEG) in InAs quantum well by setting up the Floquet states[11] to solve the time-dependent Schrödinger equation. The effect discussed in the present letter can be used to convert THz electric signals to THz magnetic ones.

We consider an InAs quantum well (QW) with its growth direction along the z-axis. A uniform THz field $\mathbf{E}_{THz}(t) = \mathbf{E}\cos(\Omega t)$ is applied along the x-axis with the period $T_0 = \frac{2\pi}{\Omega}$. By using the Coulomb gauge, we write the vector and scaler potentials into $\mathbf{A}(t) = \mathbf{E}\sin(\Omega t)/\Omega$ and $\phi(t) = 0$ respectively. Then the total Hamiltonian is $H(t) = \frac{\mathbf{P}^2}{2m^*} + H_{so}(\mathbf{P})$ with $\mathbf{P} = -i\boldsymbol{\nabla} - e\mathbf{A}(t)$ (throughout the article we take $\hbar = 1$) standing for the electron momentum operator. m^* is the effective mass of electron. For InAs QW H_{so} is dominated by the Rashba term $H_{so}(\mathbf{P}, t) = \alpha[\sigma_x \mathbf{P}_y - \sigma_y \mathbf{P}_x]$ which appears if the self-consistent potential within a QW is asymmetric along the growth direction.[12] $\boldsymbol{\sigma}$ is the Pauli matrix and α is the Rashba spin-orbit parameter which can be as large as 4×10^{-9} eV cm.[13,14] By taking the well width to be sufficiently small, one only needs to consider the lowest subband.

With the help of the Floquet states, the solution of the Hamiltonian $H(t)$ can be written as, $\Psi_{\mathbf{k},s}(\mathbf{r}, t) = \frac{1}{\sqrt{2\pi}} e^{i\mathbf{k}\cdot\mathbf{r}} \Phi_s(\mathbf{k}, t)$ with

$$\begin{aligned}\Phi_s(\mathbf{k}, t) &= e^{-i\{(E_k+E_{em})t + r_0 k_x[\cos(\Omega t)-1] - \gamma\sin(2\Omega t)\}} \\ &\quad \times \sum_{n=-\infty}^{\infty} \phi_{n,s}(\mathbf{k}) e^{in\Omega t} e^{-iq_s(\mathbf{k})t} \ . \qquad (1)\end{aligned}$$

Here $\mathbf{k} = (k_x, k_y)$ stands for the electron momentum; $s = \pm$ represents two helix spin branches; $E_{\mathbf{k}} = \mathbf{k}^2/2m^*$ is the energy spectrum of electrons; $E_{em} = \frac{e^2E^2}{4m^*\Omega^2}$ is an energy induced by the radiation field due to the DFKE; $r_0 = eE/m^*\Omega^2$; $\gamma = E_{em}/(2\Omega)$. $\phi_{n,s}(\mathbf{k}) = (\phi^{\sigma}_{n,s}(\mathbf{k})) \equiv \binom{\phi^{+1}_{n,s}(\mathbf{k})}{\phi^{-1}_{n,s}(\mathbf{k})}$ in Eq. (1) is the expansion coefficients of the Floquet states[11] of H_{so}, which gives the effect of the external THz field on the SOC with $\sigma = 1$ (-1) representing spin-up $\uparrow$ (-down $\downarrow$) in the colinear (laboratory) coordinates (along z-axis). $q_s(\mathbf{k})$ is the corresponding eigenvalue and can be determined by

$$\begin{aligned}&[n\Omega - q_s(\mathbf{k})]\phi^{\sigma}_{n,s} + \beta\sigma(\phi^{-\sigma}_{n-1,s} - \phi^{-\sigma}_{n+1,s}) \\ &\qquad + i\sigma\alpha k e^{-i\sigma\theta_{\mathbf{k}}}\phi^{-\sigma}_{n,s} = 0 \ , \qquad (2)\end{aligned}$$

in which $\theta_{\mathbf{k}}$ is the angle of the wave vector $\mathbf{k}$ and $\beta = \alpha m^*\Omega r_0/2$. All eigenvalues can be written into $n\Omega + q_s(\mathbf{k})$ with $-\Omega/2 < q_s(\mathbf{k}) < \Omega/2$. It is noted that $s = -$ branch can be determined by the $s = +$ one by $\phi^{\sigma}_{n,-} = -\sigma\phi^{-\sigma*}_{-n,+}$ and $q_-(\mathbf{k}) = -q_+(\mathbf{k})$. It is seen from Eq. (2) that due to the SOC and in the presence of a THz field, two spin branches (both helix spin branches s and colinear spin branches σ) are *strongly correlated* to each other. This correlation is a new feature due to the

†Mailing Address.

SOC and is beyond the DFKE and the sideband effect. In general, the correlation is strong when the quantity $\lambda = \beta/(\Omega/2) \geq 1$.

The retarded Green functions in momentum space at zero temperature is

$$G^r(\mathbf{k}; t_1, t_2) = -i\theta(t_1 - t_2) \sum_{s=\pm} \Phi_s(\mathbf{k}, t_1)\Phi_s^\dagger(\mathbf{k}, t_2) \quad (3)$$

and the spectral function $A = i(G^r - G^a)$ is therefore given by $A(\mathbf{k}; t_1, t_2) = \sum_{s=\pm 1} \Phi_s(\mathbf{k}, t_1)\Phi_s^\dagger(\mathbf{k}, t_2)$ which is a 2×2 matrix in the spin space. After integrating over the momentum $\mathbf{k}$, one gets $\rho(t_1, t_2) = \frac{1}{(2\pi)^2}\int d\mathbf{k} A(\mathbf{k}; t_1, t_2)$. By letting $T = (t_1+t_2)/2$ and $t = t_1 - t_2$ and transforming t to the fourier space ω,[15] one arrives at

$$\rho_{\xi_1,\xi_2}(T,\omega) = \iint_{-\infty}^{\infty} d\mathbf{k} \sum_{s=\pm} \sum_{l_1,l_2,n,m=-\infty}^{\infty} R_{\xi_1,\xi_2}(s; n, m; \mathbf{k}) e^{i(n-m)\Omega T} J_{l_1}(2r_0\mathbf{k}_x \sin(\Omega T)) J_{l_2}(2\gamma\cos(2\Omega T)) \times\delta(\omega - [E_\mathbf{k} + E_{em} - (l_1 + 2l_2 + n + m)\Omega/2 + q_s(\mathbf{k})]) \,, \quad (4)$$

in which $R_{\xi_1,\xi_2}(s; n, m; \mathbf{k}) = (\eta_{\xi_1}^\dagger \phi_{n,s}(\mathbf{k}))({\phi_{m,s}}^\dagger(\mathbf{k})\eta_{\xi_2})$ with η_ξ standing for the eigenfunction of σ_z in colinear spin system ($\xi = \sigma$) and the eigenfunction of $H(t = 0)$, *i.e.*, $\eta_s = \frac{1}{\sqrt{2}}\binom{1}{s\frac{ik_x - k_y}{k}}$, in helix spin system ($\xi = s$). It is noted that in the absence of THz field, the off-diagonal term of ρ_{ξ_1,ξ_2} vanishes in both the colinear and helix spin spaces (despite the fact that the off-diagonal term of the spectral function A in the colinear spin space is not zero). However, introducing a THz field makes it non-zero in *both* systems. A finite off-diagonal term of ρ_{ξ_1,ξ_2} indicates the correlations between the two spin branches and produces a spin polarization in the 2DEG. Similar as the diagonal term of ρ is used to express the DOS, the off-diagonal term can be used to measure the density of the spin polarization (DOSP).

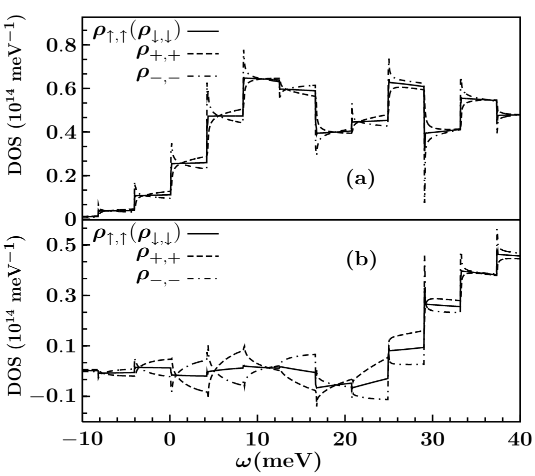

FIG. 1: The DOS at (a) $T = 0$ and (b) $T = T_0/4$ with $\Omega = 2\pi$ THz and $E = 6$ kV/cm. Solid curves: in the colinear spin space; Dashed and chain curves: in helix spin space.

From the symmetry of the Hamiltonian $H(t)$, one has $\Phi(k_x, -k_y, t) = \sigma_y\Phi(\mathbf{k}, t)$ and $\Phi(-k_x, k_y, t) = \Phi^*(\mathbf{k}, -t)$. Therefore $\rho_{\xi_1,\xi_2} = \rho^*_{\xi_2,\xi_1}$ and $\rho_{\xi_1,\xi_2}(T_0 - T, \omega) = \rho^*_{\xi_1,\xi_2}(T, \omega)$. Moreover in colinear spin space, one gets more meaningful properties: $\rho_{\uparrow,\uparrow} = \rho_{\downarrow,\downarrow}$ and $\rho_{\uparrow,\downarrow} = -\rho^*_{\uparrow,\downarrow}$. Therefore the external THz field in x-axis can only excite the time-dependent spin polarization along the y-axis for the Rashba SOC. Also from the fact that $\sum_\xi \rho_{\xi,\xi}$ does not change with the spin space, one has $\rho_{\uparrow,\uparrow} = \rho_{\downarrow,\downarrow} = \sum_s \rho_{s,s}/2$.

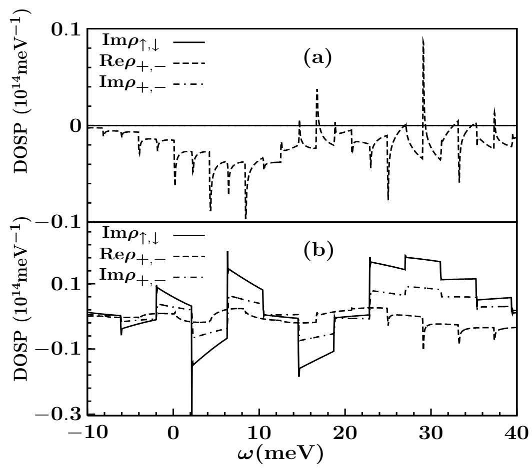

FIG. 2: The DOSP at (a) $T = 0$ and (b) $T = T_0/4$ with $\Omega = 2\pi$ THz and $E = 6$ kV/cm. Solid curves: The image part of the DOSP in the colinear spin space; Dashed and chain curves: The real and the image parts of the DOSP respectively in the helix spin space. It is noted that at $T = 0$, Im$\rho_{+,-} = 0$.

We calculate the energy and time dependence of the DOS and DOSP by numerically solving ρ_{ξ_1,ξ_2} from Eq. (4). For InAs, $m^* = 0.0239m_0$ and $\alpha = 3 \times 10^{-11}$ eV m,[13,14] with m_0 denoting the free electron mass. To show the general properties induced by the interaction between the THz field and the SOC, we choose $E \geq 1$ kV/cm and $T_0 = 1$ ps ($\Omega = 1$ THz) and 2.5 ps (0.4 tHz). With these parameters, λ is around 1, indicating a strong correlation between the two spin branches. The main results of our calculation are summarized in Figs. 1 to 3.

The DOS and DOSP are plotted in Figs. 1 and 2 in

both spin spaces at $T=0$ and $T_0/4$. The DOS shows the effects from both the intense THz field and the SOC: Both the sidebands shown as platforms in Fig. 1 and the blue-shifted main absorption edge[8] come from the intense THz fields. The Rashba SOC adds square root divergence peaks at the left edge of each sideband. It also reduces the blue shift E_{em} by roughly $m^*\alpha^2/2$. It is noted from the figure that although in the helix spin system, the two spin branches are strongly separated by the THz field and the Rashba SOC, they do not induce any spin polarization along the z-axis as in the laboratory (colinear) spin system $\rho_{\uparrow\uparrow}=\rho_{\downarrow\downarrow}$. The most striking feature of the joint effect of the THz field and the Rashba SOC comes from the *non-vanishing* off-diagonal terms of ρ, which result in the DOSP as shown in Fig. 2 in both spin spaces.

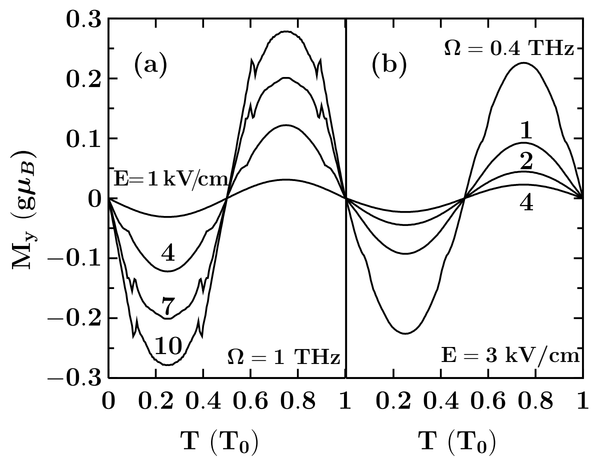

FIG. 3: The average magnetic moment M_y versus the time at $E=1$, 4, 7 and 10 kV/cm for $\Omega=1$ THz (a) at $\Omega=0.4$, 1, 2 and 4 THz for fixed $E=3$ kV/cm (b). The electron density is $N=10^{11}$ cm^{-2}.

By using $n_\sigma=\frac{1}{2\pi}\int_{-\infty}^{E_f(T)}d\omega\rho_{\sigma,\sigma}(\omega,T)$, one can determine the time-dependent Fermi energy $E_f(T)$. Then one obtains the average magnetic moment

$$\mathbf{M}(T)=\left(0,-\frac{g\mu_B}{n_\uparrow+n_\downarrow}\int_{-\infty}^{E_f(T)}d\omega\ \mathrm{Im}\rho_{\uparrow,\downarrow}(\omega,T),0\right)\ . \tag{5}$$

Due to the THz field, the Fermi energy $E_f(T)$ and the average magnetic moment $\mathbf{M}(T)$ both oscillate with the period T_0. In Fig. 3 $\mathbf{M}(T)$ is plotted as function of T for fixed THz frequency $\Omega=1$ THz and different electric field strengths $E=1$, 4, 7 and 10 kV/cm (a) and for fixed field strength $E=3$ kV/cm and different frequencies $\Omega=0.4$, 1, 2 and 4 THz (b) with the electron density $n_\uparrow=n_\downarrow=0.5\times10^{11}\mathrm{cm}^{-2}$. For these parameters, for the 2DEG, the Fermi energy is about 10 meV. It is seen from the figure that one obtains a THz magnetic signal which is induced by the THz electric one. The strength of the magnetic momentum is controlled by the electric field E for fixed Ω and by the THz frequency for fixed E. It is further pointed out that if one substitutes $E_f(T)$ with the average value over the time period into Eq. (5), one obtains the same oscillations in $\mathbf{M}$-T curves.

In conclusion we have proposed a scheme that can convert THz electric signals into THz magnetic ones by calculating the DOS and DOSP of a 2DEG with SOC and a uniform intense THz field. The magnitude of the induced magnetic signal is determined by the amplitude of the electric field. This scheme has the potential to be applied to the magnetic resonance measurement non-magnetically.

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* Author to whom correspondence should be addressed; Electronic address: mwwu@ustc.edu.cn.

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